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Active Control of Fluid-borne Noise in Hydraulic Systems Using In-series and By-pass Structures

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Abstract— The nature of digital hydraulic systems may cause severe fluid-borne noise problems because of the pulsed nature of the flow. An effective method to reduce the noise that does not impair the system performance and efficiency is needed. This article reports on initial investigations of an active valve for pressure pulsation attenuation in switched inductance hydraulic systems (SIHS) based on in-series and by-pass structures. The in-series structure represents a valve arranged in line between the SIHS and the load providing a controlled pulsating pressure drop, whilst for the by-pass structure the valve was arranged in parallel with the load providing a controlled pulsating bleed-off flow. A high-performance piezoelectric valve was used as the active controller. Adaptive notch filters with the filtered-X least mean square algorithm were applied for pressure pulsation attenuation, while a frequency-domain least mean square filter was used for secondary path identification. Simulated and experimental results show that excellent cancellation was achieved using the proposed methods, which have several advantages over passive noise control systems. Comparison of the in-series and by-pass structures is discussed in terms of system performance, robustness and advantages. The proposed control structures are very promising for fluid-borne noise cancellation in fluid power systems or other fluid systems with severe noise or vibration problems.

Keywords— digital hydraulic systems; active adaptive control; system identification; noise and vibration

I. INTRODUCTION

Switched inductance hydraulic systems (SIHS) are a type of digital hydraulic system that can be used to adjust or control flow and pressure by a means that does not rely on dissipation of power. These devices generally comprise a high-speed switching element, an inductive component and a capacitive fluid volume, as shown in figure 1 [1]. Unfortunately the inherent fast switching nature may cause severe fluid-borne noise problems. Different configurations of SIHS were proposed initially by Brown in 1987 [2]. The advantages and disadvantages of the switched hydraulic system have been studied relative to conventional orifice-metered valves. High

efficiency is the main advantage [2]. However, the fluid-borne noise (FBN) problem caused by the pulsed nature of the flow is a serious problem.

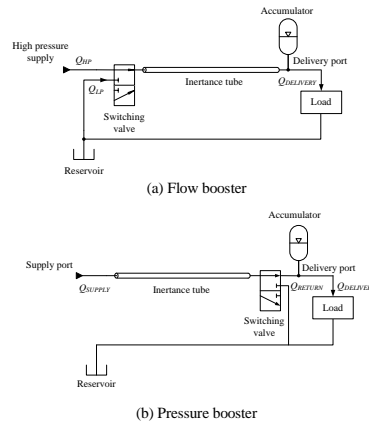


Fig. 1. Schematic diagram of SIHS

Although passive systems to reduce the FBN have been shown to be effective in many situations, their attenuation frequency range is limited and they may be bulky. Also, attenuation devices based on expansion chambers, accumulators or hoses are likely to be unsuitable for SIHS as they add compliance to the system and would impair the dynamic response. Active control methods are widely and successfully applied in the area of structure-borne noise and air-borne noise cancellation. The idea is using the intentional superposition of waves to create a destructive interference pattern such that a reduction of the unwanted noise occurs. However, applications for FBN attenuation based on the 'Active noise control (ANC) principle' are few due to the

restriction of the hardware and experimental apparatus in previous researches. In the mid-1990s, many techniques have been proposed for the purpose of pressure pulsation cancellation using active noise control method [3,4]. Maillard studied the active control of pressure pulsation in piping system where the filtered-X least mean square was used as the control algorithm [3]. Kojima and others proposed an active noise attenuator for pressure pulsation in filled-fluid piping systems, and good experimental results were achieved [4]. In 2008, an active FBN attenuator was designed and applied successfully in a piping system by Wang based on a servo-valve as an anti-noise actuator [5]. Pan et al. proposed an adaptive FBN controller in parallel with a digital hydraulic system and successfully implemented [6]. In the present paper, two different control structures, in-series and by-pass, are implemented in simulation and experimentally, and compared and discussed.

II. ACTIVE ADAPTIVE SYSTEM WITH FXLMS ALGORITHM

A. Filtered-X Least mean square algorithm

The least-mean square (LMS) algorithm is a linear adaptive filtering algorithm, which generally consists of a filtering process and an adaptive process [7]. In general there are two filter structures that can be applied for adaptive filtering: finite impulse response (FIR) and infinite impulse response (IIR) structures. Figure 2 shows a block diagram of a standard cancellation system employing the conventional LMS algorithm.

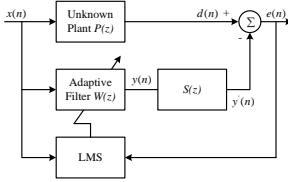


Fig. 2. Simplified block diagram of ANC system [8]

Three basic relations can be used to describe the LMS algorithm simply and equivalently as follows [7]

$$1. \text{ Filter output: } y(n) = \mathbf{w}^T(n)\mathbf{x}(n) \quad (1)$$

$$2. \text{ Error signal: } e(n) = d(n) - y(n) \quad (S(z) = 1) \quad (2)$$

$$3. \text{ Filter coefficients adaptation: } \mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{x}(n)e(n) \quad (3)$$

At each iteration or time update, the LMS algorithm requires knowledge of the most recent values: $\mathbf{x}(n)$, $d(n)$ and $\mathbf{w}(n)$. The iterative procedure is started with an initial guess $\mathbf{w}(0)$. In figure 2, the introduction of the actuator dynamics $S(z)$ into a controller will generally cause instability [8]. This is because the error signal is not ideally "aligned" in time with the reference signal due to the presence of $S(z)$ [9].

Morgan proposed a solution which is placing an identical filter in the reference signal path to the weight update of the

LMS algorithm to solve this problem. The reference signal is filtered so as to compensate for the effect of the secondary path in the adaptation loop. This algorithm is, using the widely realized and named-filtered-X LMS (FXLMS) algorithm, as shown in figure 3. The details of the FXLMS algorithm can be found in [9].

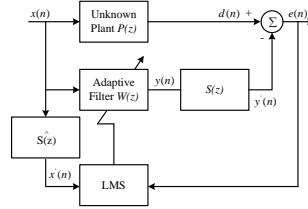


Fig. 3. Block diagram of ANC system using the FXLMS algorithm [9]

B. Narrowband control system

In a narrowband feedforward ANC system, the reference signal can be generated by detecting the fundamental frequency of the primary noise from nonacoustic sensors, such as a tachometer or accelerometer. This reference signal is completely unaffected by the feedback effects from the secondary source [9]. Figure 4 shows the block diagram of a Filtered-X adaptive notch filter for narrowband noise cancellation.

Two orthogonal components $x_0(n)$ and $x_1(n)$ are used as reference signals for the two-weight adaptive notch filter and the control signal $y(n)$ is summed from the weighted reference inputs. For the frequency present in the reference signal, the adaptive weight vector $\mathbf{w}(n) = [w_0(n), w_1(n)]$ is required for cancellation. The weights are updated by the equations:

$$\mathbf{w}_0(n+1) = \mathbf{w}_0(n) + \mu \mathbf{x}'_0(n)e(n) \quad (4)$$

$$\mathbf{w}_1(n+1) = \mathbf{w}_1(n) + \mu \mathbf{x}'_1(n)e(n) \quad (5)$$

where $\mathbf{x}'_0(n)$ and $\mathbf{x}'_1(n)$ are the reference signals filtered by the cancellation path estimate $\hat{S}(z)$.

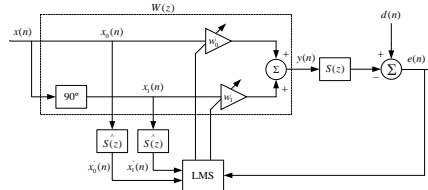


Fig. 4. Single-frequency ANC system using FXLMS algorithm [9]

The cancelling signal $y(n)$ is given by:

$$y(n) = w_0(n)x_0(n) + w_1(n)x_1(n) \quad (6)$$

Periodic noise usually contains tones at the fundamental frequency and at several harmonic frequencies. These multiple

sinusoidal interferences can be cancelled by extension of the basic adaptive notch filter technique to multiple notches. For the case in which the undesired primary noise contains M harmonics, M two-weight adaptive filters can be connected in parallel to cancel these periodic components.

The reference inputs are now given by

$$x_m(n) = A_m \cos(\omega_m n \Delta t) \quad m = 1, 2, \dots, M. \quad (7)$$

The cancelling signal is a sum of M adaptive filter outputs

$$y(n) = \sum_{m=1}^M y_m(n), \quad m = 1, 2, \dots, M. \quad (8)$$

$$y_m(n) = \mathbf{w}_{m,0}(n) \mathbf{x}_{m,0}(n) + \mathbf{w}_{m,1}(n) \mathbf{x}_{m,1}(n) \quad (9)$$

where m is the channel index.

The weights are updated by the equations:

$$\mathbf{w}_{m,0}(n+1) = \mathbf{w}_{m,0}(n) + \mu \mathbf{x}'_{m,0}(n) e(n) \quad (10)$$

$$\mathbf{w}_{m,1}(n+1) = \mathbf{w}_{m,1}(n) + \mu \mathbf{x}'_{m,1}(n) e(n) \quad (11)$$

where $\mathbf{x}'_{m,0}(n)$ and $\mathbf{x}'_{m,1}(n)$ are the reference signals filtered by the cancellation path estimate $\hat{S}(z)$.

C. Secondary path on-line identification

Assuming that the characteristics of $S(z)$ are time-invariant, the off-line modelling technique can be applied to estimate the secondary path dynamics $S(z)$. For this technique, the process data is first stored in a data storage medium then transferred to a controller and evaluated [9]. In situations where the secondary path $S(z)$ is unknown and time-varying, the identification must proceed in parallel with the cancellation algorithm, as shown in figure 5. The auxiliary random noise technique is applied for secondary path identification in this paper. It was firstly proposed by Eriksson for ANC and applied successfully for ABN and SBN applications [11]. It involves injection of auxiliary random noise into the system in order to estimate the dynamics of secondary path $S(z)$. The power of the auxiliary signal should be small in comparison with the power of the primary noise. Also the auxiliary signal should be a zero-mean signal which is independent of the primary noise [12].

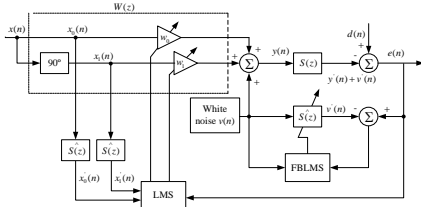


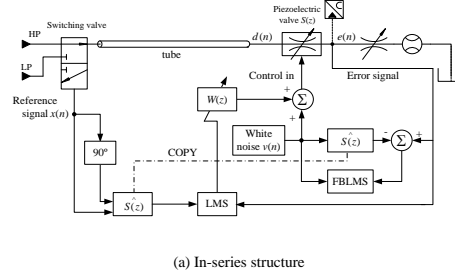
Fig. 5. Single-frequency ANC system using FXLMS and FBLMS algorithms

The advantage of this method is that $\hat{S}(z)$ obtained by the model at all frequencies is signal-independent. This brings the benefit of fast response of the controller to the changes of the

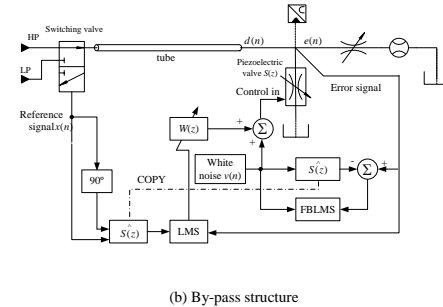
system primary noise [12]. The fast-block least-mean square (FBLMS) algorithm in frequency domain is applied in secondary path identification [7].

III. CONTROL STRUCTURES AND SIMULATION

The noise caused by the switching nature in a SIHS is a typical narrowband signal and its fundamental frequency is determined by the switching frequency of the valve which is a known input. Thus, the fundamental frequency of the reference signal $x(n)$ can be obtained for the noise controller. A high-performance piezoelectric valve was used as the secondary source. It essentially produced a secondary flow or pressure pulsation, in anti-phase with the primary system pulsations produced by the SIHS, to cancel the pressure pulsations at the load. For the in-series structure the valve was arranged in line between the SIHS and the load providing a controlled pulsating pressure drop, as shown in figure 6 (a), whilst for the by-pass structure the valve was arranged in parallel with the load providing a controlled pulsating bleed-off flow, as shown in figure 6(b). The pressure transducer arranged at the downstream of the piezoelectric valve in the in-series structure and at the conjunction of the tube and piezoelectric valve in the by-pass structure was used to measure the error signal $e(n)$. A zero-mean white noise $v(n)$ was applied for the online secondary path identification.



(a) In-series structure



(b) By-pass structure

Fig. 6. Block diagram of the in-series and by-pass structures of SIHS

A simulation model was created using MATLAB Simulink. The Transmission Line Method (TLM) was used to model the tube dynamics. The model was developed by Krus et al [13] and modified by Johnston [14, 15] to include unsteady or

frequency-dependent friction. The high-speed switching valve was modeled using the standard orifice equation, as shown in equation (12). The high-performance piezoelectric valve was modelled by using a standard orifice equation and a second order transfer function with a natural frequency of 628 rad/s and a damping ratio of 0.8 to represent the dynamics of the valve.

$$q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \operatorname{sgn} \Delta p \quad (12)$$

where C_d is the discharge coefficient of valve, A is the valve opening area and Δp is the pressure drop of the valve. Parameters for the simulation models are listed in Table I.

TABLE I. PARAMETERS FOR SIMULATIONS

Bulk modulus in valve B_v	10^9 Pa
Density ρ	870 kg/m^3
Viscosity μ	20 cSt
Switching frequency f	40 Hz
High supply pressure P_{HP}	100 bar
Low supply pressure P_{LP}	10 bar
Reservoir pressure P_r	1 bar
Effective orifice area A_o , switching valve open	1.44 cm^2
Effective orifice area A_c , switching valve closed	0.03 mm^2
Valve internal volume between switching orifices and inertance tube, V_{va}	10 cm^3
Discharge coefficient of the loading valve	0.7
Opening of the loading valve A_L	0.1 cm^2
Opening of the piezoelectric valve A_{piezo}	0.02 cm^2
Inertance tube length l	1 m
Inertance tube diameter d	7.1 mm
Bulk modulus in tube B_t	1.6×10^9 Pa
Number of unsteady friction terms	4

For the in-series structure, the standard deviation of white noise $v(n)$ was $1 \times 10^{-6} \text{ m}^2$ and the convergence factor was $\mu=1 \times 10^4$ for the online identification filter. The length of the identification filter was 256. Three notch filters were applied in parallel for different harmonics of 40Hz, 80Hz and 120Hz. Figure 7 shows the amplitudes of original pressure ripples and the cancellation. The maximum cancellation 41.2dB was achieved at the frequency of 40Hz. The average cancellation of three harmonics was 27.8dB.

Good cancellation of FBN in simulation leads to the conclusion that the designed noise controller is effective for noise attenuation with the proposed in-series structure. However, the introduction of white noise could affect the controller performance. Besides, increased power consumption is expected for two reasons. Non-zero load flowrate is essentially necessary since the controller relies upon a pressure drop across the piezoelectric valve for cancellation. Moreover, the mean supply pressure would increase as the piezoelectric valve would result in a pressure drop. Based on these, a high-speed valve with high flowrate and low pressure drop is desired in terms of the canceller requirement and system efficiency with this structure.

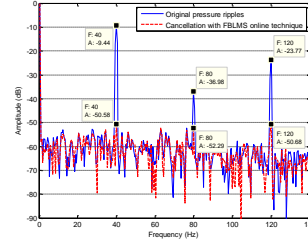


Fig. 7. Simulated multiple harmonics cancellation of FBN using FBLMS online identification with in-series structure

For the by-pass structure, the standard deviation of white noise was $1 \times 10^{-5} \text{ m}^2$ and the convergence factor of the identification filter was $\mu=1$. The power of white noise is larger than that was used in the in-series structure, which resulted in the smaller convergence factor in order to achieve the similar convergence speed of identification. The power of the white noise applied should be small in comparison with the power of the primary noise. This can be estimated by using simulation. Same parameters were re-applied in simulation.

Figure 8 shows the amplitudes of original pressure ripples and the cancellation for five harmonics. The maximum cancellation 73.5 dB was achieved at the frequency of 40Hz. The average cancellation of five harmonics was 44.6dB. The by-pass structure is more effective and stable than the in-series structure.

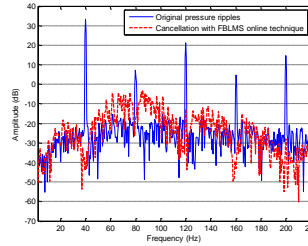


Fig. 8. Simulated multiple harmonics cancellation of FBN using FBLMS online identification with by-pass structure

IV. EXPERIMENTAL STUDIES

The experimental tests were conducted on two different rig structures with the FBN cancellation valve in series and by-pass configurations. A novel piezoelectric valve was used as the actuator to produce the anti-noise in the system because it had a fast response and high bandwidth [16]. A PI E-481 high-power piezo-amplifier was used to drive the piezoelectric actuator. The designed controller was implemented on a dSPACE DS1005 controller system with a DS2002 A/D board and a DS2103 D/A board.

The experimental test rig with the in-series structure is shown in Figure 9, where the piezoelectric valve is arranged in

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line with the rigid tube and the loading valve. A pressure transducer with a range to 50 bar was fixed after the piezoelectric valve to measure the delivery pressure of the system.

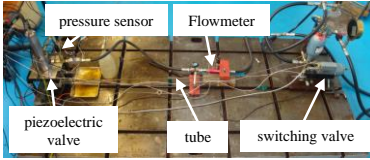


Fig. 9. Photograph of the experimental test rig with the in-series structure

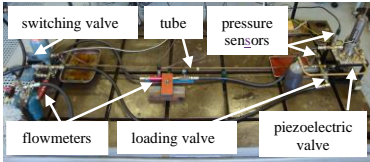


Fig. 10. Photograph of the experimental test rig with the by-pass structure

Figure 10 shows a photograph of the experimental test rig with the by-pass structure. For the by-pass structure, a pressure transducer with a range of 135bar was arranged at the conjunction of the tube and piezoelectric valve. A flowmeter was fixed at the downstream line of the piezoelectric valve to measure the flowrate passing through the by-pass branch. In both systems a pre-determined pulsed signal was generated to control the switching servo valve. In order to avoid bias of the error signal, a digital high pass filter was built based on dSPACE with 1Hz cut-off frequency. A flowmeter was fixed after the loading valve to measure the load flowrate.

Figure 11 shows the cancellation at the harmonics of 40Hz, 80Hz and 120Hz based on the in-series structure. It can be seen that the maximum cancellation of 44.3dB occurred at the frequency of 120Hz. The average cancellation was over 30dB. The convergence factors applied in the paralleled adaptive notch filters were listed in Table II.

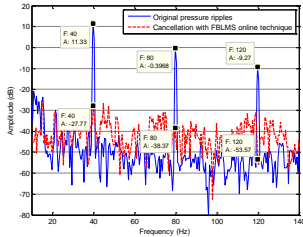


Fig. 11. Experimental multiple harmonics cancellation of FBN using FBLMS online identification with in-series structure

TABLE II. CONVERGENCE RATES USED FOR DIFFERENT HARMONICS FOR AN IN-SERIES STRUCTURE IN EXPERIMENTS

Frequency (Hz)	40	80	120
Convergence rate μ_c	6×10^{-3}	6×10^{-3}	6×10^{-3}

Figure 12 shows the cancellation at the harmonics of 40Hz, 80Hz and 120Hz based on the by-pass structure. The convergence rates applied in the paralleled adaptive notch filters were listed in Table III. As can be seen, the maximum cancellation of 35.2dB occurred at the frequency of 120Hz and the average cancellation was also over 30dB.

TABLE III. CONVERGENCE RATES USED FOR DIFFERENT HARMONICS FOR A BY-PASS STRUCTURE IN EXPERIMENTS

Frequency (Hz)	40	80	120
Convergence rate μ_c	5×10^{-4}	7×10^{-4}	3×10^{-4}

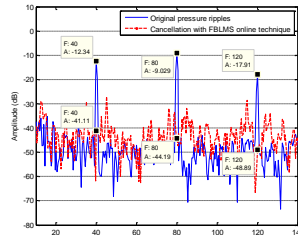


Fig. 12. Experimental multiple harmonics cancellation of FBN using FBLMS online identification with by-pass structure

Figure 12 shows the cancellation at the harmonics of 40Hz, 80Hz and 120Hz based on the by-pass structure. As can be seen, the maximum cancellation of 35.2dB occurred at the frequency of 120Hz and the average cancellation was also over 30dB.

V. DISCUSSION AND CONCLUSION

The designed FBN controller with the in-series and by-pass structures performs effectively and robustly. Based on the simulated and experimental results, the following statements can be made:

- The designed controller with the in-series and by-pass structures is able to attenuate the FBN effectively and adapt quickly with varying conditions. It is capable of maintaining stable performance when the switching frequency is varied.
- The introduction of white noise would increase the background noise but the cancellation should still be acceptable compared with the peak amplitude at the cancelled frequencies. However, it can be found that the amplitude of background noise from the by-pass structure was lower than from the in-series structure. Less effects caused by the white noise were observed when the noise controller was arranged as a by-pass to the main system.

- For the by-pass structure, load pressure is required for the noise controller to generate the anti-noise signal; whilst load flowrate is required for the noise attenuator for the in-series structure. That means the in-series structure would have a limitation when there is lack of flow passing through the piezoelectric valve. In that case the piezoelectric valve cannot provide enough power for FBN cancellation. The by-pass structure is not restricted by the structure itself because the noise problem is only considered with the presence of the load pressure. FBN may not be a problem when there is no load pressure in the system.

- For the in-series structure, with the fixed supply and return pressures, the mean delivery pressure would decrease in the process of controlling because pressure drop occurred in the piezoelectric valve. The ideal controller should have a high flowrate and small pressure drop. This is expected to decrease the power consumption of the controller. For the by-pass structure, the mean delivery flowrate would decrease when the attenuator is switched on. This is because a by-pass flowrate is needed for the piezoelectric valve.

- The bypass structure can be implemented using a valve with a high bandwidth, high pressure drop and low flowrate, and this can be achieved by many commercial devices. However the in-series structure requires a valve with a high bandwidth, high flowrate and low pressure drop. This combination is difficult to achieve and would probably require a large, expensive, specialised valve.

Table IV briefly describes the comparison between the by-pass and the in-series structures.

TABLE IV. CONVERGENCE RATES USED FOR DIFFERENT HARMONICS FOR A BY-PASS STRUCTURE

	By-pass structure	In-series structure
FBN cancellation	Good	Good
Stability and robustness	Good	Good
Background noise	Small	Medium
Effects from the opening of control valve	Small	Highly relatedaffected
Flowrate requirement	No	Yes
Pressure requirement	Yes	Yes

It can be concluded that the by-pass structure can be more widely and effectively used for FBN cancellation in hydraulic systems compared with the in-series structure. Also less effect comes from the auxiliary noise which was used for secondary path identification and the opening of control valve within this structure. Moreover, it does not require flowrate passing through the control valve. Therefore, the by-pass structure can be seen as a general and effective approach for FBN cancellation with good performance and few limitations.

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